Preface

The process by which a massive compact object (like white dwarfs, neutron stars, black holes etc) gravitationally captures ambient matter is called accretion. The accretion of matter on to a compact massive star is the likely source of energy in the observed binary X-ray sources. Since black holes are 'black', there cannot be any direct observational evidence of them. Thus they must be observed by detecting the radiations emitted by accreting matter. For typical gas dynamical conditions found in the interstellar medium and in the matter exchanged between the binary stars, it is expected that accretion flows on to compact objects will be hydrodynamical or magneto-hydrodynamical in nature. Thus, to study black hole accretion, it is necessary to know the hydrodynamic properties of the flow of the matter as it is the matter which, after all, will emit the radiation that we detect by satellites. The variation of thermodynamic quantities such as the initial energy density of the accreted matter plays important roles as the emitted radiation intensity from the flow depends on the density and the temperature at each point of the flow at each moment of time. So the spectral and temporal properties of emitted radiations are directly determined by the hydrodynamical variables.

In my Ph.D. work, I mainly made effort to study the hydrodynamic properties of the flow and its stability properties through time-dependent numerical simulations. We started with time-dependent solutions of one-dimensional (spherically symmetric) and two-dimensional (axially symmetric) accretion flows around compact objects, in particular black holes, after examining the steady-state solutions. We describe the development of a two-dimensional hydrodynamic code and its application to various astrophysical problems. A FORTRAN code for two-dimensional numerical hydrodynamics has been developed to model viscous accretion discs. We employ a grid-based finite difference method called the total variation diminishing method (TVD). The effective shear viscosity present in the code is evaluated. The simulations were carried out for flows in the Schwarzschild geometry. By numerical simulation, we show that the theoretical solutions (with or without shocks) which are claimed to be stationary are indeed so. When the shocks are absent, they show steady oscillations. Our survey was carried out using the entire inflow parameter space spanned by the specific energy, angular momentum, shear viscosity and a power-law cooling. It is believed that high-viscosity flows reside on the equatorial plane, and supply low energy X-rays, while the low-viscosity and low-angular-momentum flows fall rapidly on to the black holes away from the equatorial plane and have little time to radiate X-rays. However, they can energise low-energy photons and produce hard X-rays and contribute to the spectrum of black holes candidates. In the thesis work, for the first time, numerically we have simulated two-component advective flows (TCAF) where a cold Keplerian disc is surrounded by hot sub-Keplerian flow. Interestingly, we have found the stability of this flow. It is believed that the soft-photons originated from the low-temperature Keplerian discs are reprocessed by the hot electrons of CENBOL through the inverse-Comptonisation process. They are emitted as hard X-rays. Thermal pressure gradient force at the shock location becomes significant in the transverse direction which drives matter upward and downward in the from of jets or outflows. These X-rays and outflows are observed.

Accretion flow dynamics during an outburst phase of transient BHCs can be explained by a model analysis of spectral and temporal behaviour of the source. The spectral and temporal properties of the black hole candidates can be explained using several models, which generally include two components, namely a Keplerian disc and a hot corona, only the nature of the corona varies from model to model. In the observational prospect, TCAF model requires two accretion rates, namely the Keplerian disc accretion rate and the halo accretion rate, the latter being composed of a sub-Keplerian, low-angular-momentum flow which may or may not develop a shock. In this solution, the relevant parameter is the relative importance of the halo (which creates the Compton cloud region) rate with respect to the Keplerian disc rate (soft photon source). Since last decade, TCAF model has been used to manually fit data of several black hole candidates quite satisfactorily. Quasi-periodic oscillations (QPOs) observed in X-rays are very important features for the study of accreting black holes. Observations and possible explanations of QPOs in black hole candidates have been reported quite extensively in the literature. Low- and intermediate-frequency QPOs in black hole candidates are believed to be due to oscillations of the shocks, i.e. Comptonising regions in an accretion flow. Using our simulated TCAF, one can numerically simulate the light curves emitted from an accretion disc for different accretion rates and also can find how the QPO frequencies vary. Thus the explanations of spectral and timing properties of galactic and extra-galactic black holes based on TCAF models appear to have firm foundation.

In Chap. 1, we explain the terms associated with the title of the thesis. First, we discuss the general view of accretion processes around compact objects, in particular around black holes. Then, we point out the basic properties of accretion around non-rotating black holes. In case of the black hole physics, a full general relativistic approach is recommended, but it makes the time-dependent hydrodynamic equation which includes radiative transfer very complex. This problem is circumvented using a pseudo-Newtonian potential. We briefly discuss the governing equations for fluid dynamical study in a pseudo-Newtonian geometry. Subsequently, we discuss the mathematical aspects of shock waves and their presence in accretion processes. Historical studies of spherical accretion process through various approaches are briefly presented. We start with the Bondi flow for spherical accretion of an ordinary star. A qualitative discussion on the development of disc accretion process is also presented. We then discuss the standard Keplerian disc model. This model explains the nature of the multi-colour soft X-ray spectrum very well but it fails to explain very high-energy radiation coming from the stellar mass black holes and distant Quasars and AGNs. This brings the advective flows in the picture. This component has lower angular momentum than a Keplerian disc, and is called a sub-Keplerian flow. A realistic accretion flow may have both the components, a sub-Keplerian flow surrounding a Keplerian flow. This is the so-called two-component advective flow or TCAF model of Chakrabarti and Titarchuk.

In Chap. 2, we give an overview on the past works done on numerical simulation for accretion flows around black holes. We start with non-viscous cases. We also point out some important simulations of viscous accretion discs. In the last Section of this Chapter, we present the precise goals for this thesis work.

Chapter 3 describes the numerical methods employed to model accretion flows and their implementation in a FORTRAN code. We present all the governing equations for both non-viscous and viscous flows. We discuss the solution technique for a non-viscous system. Subsequently, we give all the schemes to incorporate turbulent viscosity in the non-viscous system. Finally, we add a power-law cooling in our viscous system and study the properties.

In Chap. 4, we pointed out the procedure of simulation and the computational box in details. We study the accretion processes on a black hole by numerical simulation. We use a grid-based finite difference code for this purpose. Tests of the code are made using the flow without angular momentum, namely, the Bondi flow.

In Chap. 5, we scan the parameter space spanned by the specific energy and the angular momentum of the inflow and compare the time-dependent solutions with those obtained from theoretical considerations. We found several important results: (a) The time-dependent flow behaves close to a constant height model flow in the pre-shock region and a flow in vertical equilibrium in the post-shock region. (b) The infall time scale in the post-shock region is several times longer than the free-fall time scale. (c) There are two discontinuities in the flow, one being just outside of the inner sonic point. Turbulence plays a major role in determining the locations of these discontinuities. (d) The two discontinuities oscillate with two different frequencies and the post-shock flow behaves as a coupled harmonic oscillator. A Fourier analysis of the variation of the outer shock location indicates a higher power at the lower frequency and lower power at the higher frequency. The opposite is true when the analysis of the inner shock is made. These behaviours will have implications in the spectral and timing properties of the black hole candidates.

In Chap. 6, we study the time evolution of a rotating, axisymmetric, viscous accretion flow around black holes using a grid-based finite difference method. We use the Shakura-Sunyaev viscosity prescription. However, we compare with the results obtained when all the three independent components of the viscous stress are kept. We show that the centrifugal pressure-supported shocks become weaker with the inclusion of viscosity. The shock is formed farther out when the viscosity is increased. When the viscosity is above a critical value, the shock disappears altogether and the flow becomes subsonic and Keplerian everywhere except in a region close to the horizon, where it remains supersonic. We also find that as the viscosity is increased, the amount of outflowing matter in the wind is decreased to less than a percentage of the inflow matter. Since the post-shock region could act as a reservoir of hot electrons or the so-called Compton cloud, the size of which changes with viscosity, the spectral properties are expected to depend on viscosity strongly: the harder states are dominated by low-angular momentum and the low-viscosity flow with significant outflows while the softer states are dominated by the high-viscosity Keplerian flow having very little outflows.

In Chap. 7, we carry out a series of numerical simulations of viscous accretion flows having a reasonable spatial distribution of the viscosity parameter. We add the power-law cooling throughout the flow. We show that in agreement with the theoretical solutions of viscous transonic flows, matter having viscosity parameter above a critical value becomes a Keplerian disc while matter having lesser viscosity remains a low-angular momentum, sub-Keplerian flow. The latter component produces centrifugal pressure-supported shock waves. Thus, for instance, the flows having sufficiently high viscosity on the equatorial plane and low viscosity above and below, produce a Two-Component Advective Flow (TCAF) where a Keplerian disc is surrounded by a rapidly moving sub-Keplerian halo. We find that the post-shock region of the Keplerian disc is evaporated and the configuration is stable. This agrees with the theoretical models which attempt to explain the spectral and timing properties of black hole candidates.

Finally, in Chap. 8, we draw concluding remarks and briefly mention our future plans.

http://www.springer.com/978-3-319-09539-4

Numerical Simulation of Viscous Shocked Accretion Flows Around Black Holes
Giri, K.
2015, XXII, 129 p. 54 illus., 8 illus. in color., Hardcover
ISBN: 978-3-319-09539-4